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14. ABSTRACT

The High Fidelity Simulation of Littoral Environments (HFSoLE) Challenge Project (C75) encompasses a suite of seven oceanographic models capable of exchanging information in a physically meaningful sense across the littoral environment. This project is leveraging and extending state-of-the-art atmospheric, oceanographic, estuarine, riverine, surface water/groundwater, and sediment transport models to provide DoD with the technology capable of rapidly characterizing the littoral environment. Applications of these models include real world scenarios such as predicting the ocean currents off the Spanish Coast after the Prestige oil spill and generating diver visibility maps for the Persian Gulf These models and their inputs have been finely tuned, tested, analyzed, and coupled with the use of HPC Challenge time.

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High Fidelity Simulation of Littoral Environments: Applications and Coupling of Participating Models

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Abstract

The High Fidelity Simulation of Littoral Environments (HFSoLE) Challenge Project (C75) encompasses a suite of seven oceanographic models capable of exchanging information in a physically meaningful sense across the littoral environment. This project is leveraging and extending state-of-the-art atmospheric, oceanographic, estuarine, riverine, surface water/groundwater, and sediment transport models to provide DoD with the technology capable of rapidly characterizing the littoral environment.

Applications of these models include real world scenarios such as predicting the ocean currents off the Spanish Coast after the Prestige oil spill and generating diver visibility maps for the Persian Gulf. These models and their inputs have been finely tuned, tested, analyzed, and coupled with the use of HPC Challenge time.

1. Introduction

In recent decades, the littoral environment has continued to become an area of great importance to the Department of Defense research and ultimately operations. The HFSoLE Portfolio was funded under the Common High Performance Software Support Initiative (CHSSI) of the Department of Defense (DoD) High Performance Computing Modernization Program (HPCMP) to combine littoral environmental models via model coupling within the framework of the DoD's most powerful computational environments. The C75 Challenge Project enhances the development and application of participating models as well as their coupling.

The HFSoLE effort is broken into 4 projects: 1) The System Integration and Simulation Framework Project is developing interface models and is composed of two sub-projects: Multi-level Parallelization as tested with the Navy Coastal Ocean Model (NCOM) and the Model Integration Framework under which the Model Coupled Environmental Library (MCEL) has been developed. 2) The Near-shore and Estuarine Environments Project is coupling and enhancing nearshore process models to efficiently simulate interactions between winds, waves, currents, tides, water levels, and sediment transport. This project contains three sub-projects: Simulation of Surf Zone Waves and Currents which uses the STWAVE model, a steady-state finite-difference model based on the wave action balance equation; Simulation of Coastal and Estuarine Circulation which uses The ADCIRC Model, an ADvanced CIRCulation Model for Shelves, Coastal Seas and Estuaries; and the Near-Shore Sediment Transport sub-project which focuses on improvements to the capabilities and parallelization of the LSOM (Littoral Sedimentation and Optical Model). 3) The Surface Water/ Groundwater, Riverine and Tidal Environments Project is enhancing the capabilities of the Adaptive Hydraulics

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(ADH) model. The sub-projects Scalable Modeling of Tidal Riverine Environments and the Advanced Surface Water-Groundwater Connectivity with Linkage to Atmospheric Outputs both use the ADH model. This project is working toward providing DoD the tools to generate fast and accurate estimates of water depths andvelocity distributions for use in ingress/egress assessment for rivers and streams, flow rate and sediment loading as input for coastal simulation, and ground-surface inundation and moisture content predictions for use in local atmospheric simulations. 4) Lastly, the System Applications Project is improving the fidelity and execution speed of DoD maritime operation simulation systems dependent on data from ocean surface behavior models. The Simulation of Waves Nearshore (SWAN) model has been used for testing in this component. Such simulations include amphibious assault, mine clearing and sea keeping operations. This project provides for the development, implementation and testing of an environmental server to support Modeling & Simulation (M&S).

2. Problem and Methodology

2.1. Coupling/MCEL.

The HFSoLE Portfolio is developing a scalable software suite of linked dynamic models for real-time operational applications and high fidelity simulations for M&S scenarios. The C75 Challenge Projects allows for the development of MCEL to adapt to coupling such an extensive array of models as an alternative to file-based approaches. Three coupled model groups: 1) HYCOM and NCOM; 2) ADCIRC, LSOM, and SWAN; and 3) ADH and STWAVE are used to assess the utility of MCEL for coupled model applications.

ADCIRC-SWAN-LSOM Coupling

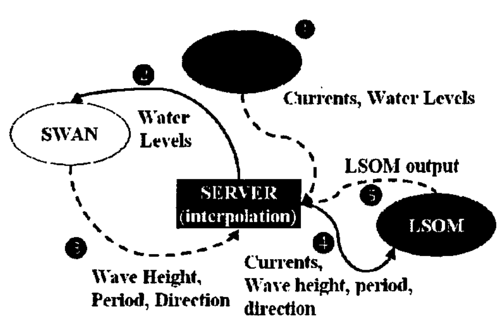

Figure 1. One coupled model application. The ADCIRC, LSOM, and SWAN models send data to the MCEL server (red dashed arrows) while LSOM and SWAN receive data back from MCEL (solid black arrows) in the course of coupling.

The value of the models participating in the HFSoLE Portfolio has been evident during this Challenge Project year by all of the planned and unplanned applications that have generated requests for the model outputs.

2.2. Applications/Data assimilation, River Database, and Boundary Conditions.

HYCOM and NCOM can be run at a range of horizontal scales in order to provide boundary conditions to specific sub-regions. Extensive development, testing, and analysis has been done on the 1/8 degree global version of NCOM (Martin, 2000) to improve its capability to provide boundary conditions. A different preparation of files for data assimilation into the global NCOM real-time system (Rhodes et al, 2002) has been tested. Specifically, the difference between the climatological of Modular Ocean Data Assimilation System (MODAS) mean and Navy Layered Ocean Model (NLOM) mean has been taken into account. A river database has been developed and tested for a 5 year model run of global NCOM to assess the impact of these inputs into a global model (Barron and Smedstad, 2002). HYCOM also uses the river database to provide monthly river freshwater fluxes. Furthermore, this database is included in the Atlantic/Pacific HYCOM simulations under the Challenge Project Basin-scale Prediction with the Hybrid Coordinate Ocean Model (C79).

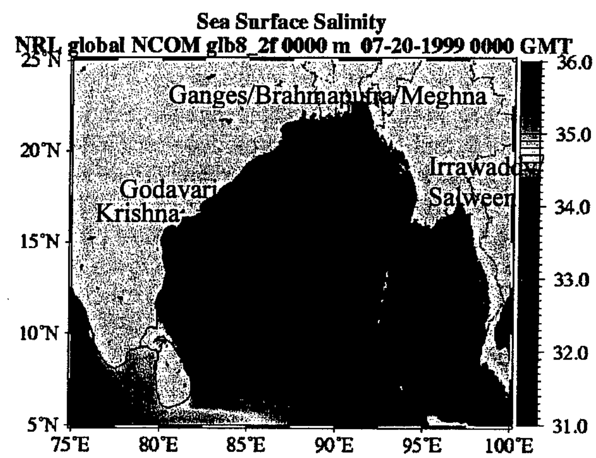

Figure 2. Signatures of river outflow resulting from the river database forcing are seen in the salinity fields.

2.3. Applications/Nearshore/Surf Zone Wave and Current Modeling.

The simulation of hydrodynamics in the very nearshore is needed for both military (e.g., JLOTS and mine/countermine activities) and civilian projects (e.g., design of beach protection and restoration projects). In the nearshore region, hydrodynamic processes from estuaries, inlets, the surf zone and offshore waters all interact, necessitating coupled model dynamics associated with waves, water levels, and currents. As an element of the HFSoLE Challenge Project, the nearshore transformation model STWAVE has been validated for a number of environments, including an eastern US coastal beach, a western US tidal inlet, and a controlled laboratory environment.

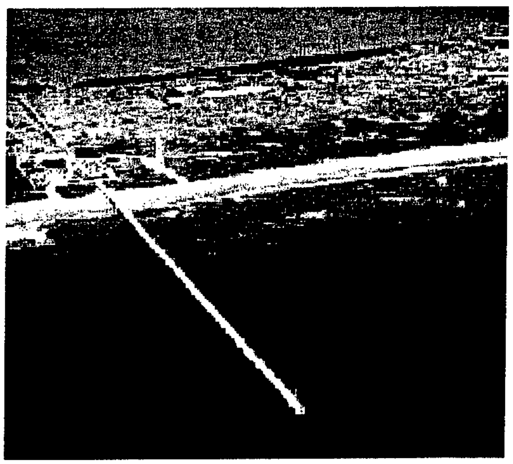

Figure 3. The eastern US coastal beach at Duck, North Carolina, one location for STWAVE validation.

2.4. Applications/Prestige Oil Spill.

Two models in the suite of Challenge Project models, global NCOM and ADCIRC provided oceanographic products upon request by Spanish researchers at Puertos Del Estado (PE) for support in the wake of the *Prestige* oil spill in the Fall-Winter, 2002. Global NCOM provided boundary conditions to a nested Princeton Ocean Model (POM). PE requested NRL output from their pre-operational global NCOM model. The ADCIRC model generated tidal and wind –driven currents in shallow coastal areas that were then utilized by the NOAA oil spill model, GNOME.

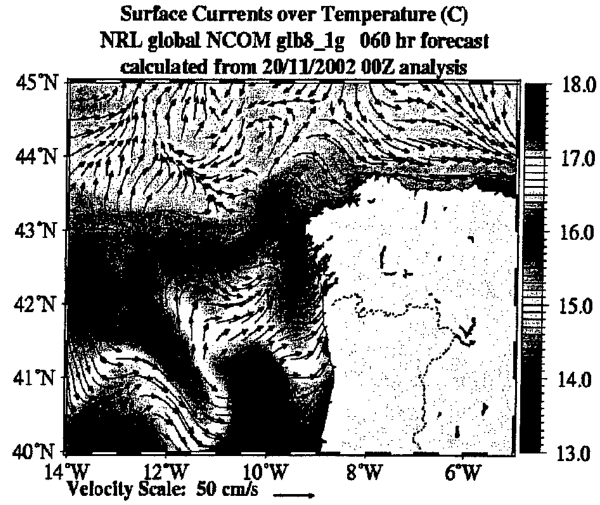

Figure 4. Surface current fields extracted from global NCOM for the area affected by the *Prestige* oil spill.

2.5. Applications/Arabian Gulf.

The same two model systems, NCOM and ADCIRC were applied in support of *Operation Iraqi Freedom* in March of 2003. Two NCOM systems: global 1/8° NCOM (NCOM G8) and nested re-locatable NCOM were applied to predict currents in the Persian Gulf. The resolution of global NCOM is about 15 km in the Persian Gulf. To provide higher-resolution coverage and include the effect of tidal forcing, re-locatable NCOM nests were applied. These were the first real-time support applications of the nested re-locatable NCOM system, still in the early stages of development that began in FY03.

A forecast system was developed using the MPI 2D/3D ADCIRC coastal circulation model. The ADCIRC system simulated tidal currents at resolutions down to 2 m in the region of the Shat-Al-Arab river (KAA).The forecast system was fully automated including set-up, execution, and product generation (Blain and Edwards, 2002). The model was run on 160 processors of the ARL classified IBM SP4. Time to completion for a 17 day, tidally driven 48-hr forecast run (which included a 15 day spin-up period) was approximately 12 hours.

The approach was to develop a limited domain model of the KAA region that would be forced offshore by a larger domain, previously developed, ADCIRC model of the Persian Gulf (Blain, 1998). The ADCIRC model utilizes a finite element discretization allowing the use of highly flexible unstructured grids. The size of the mesh (247,767 nodes and 480,001 elements) allowed for resolution ranging from 2 m to 1 km. Parallelization of the 480,000 element grid for the KAA application was vital to its success in meeting operational time restraints for daily forecast products. The model portability across

HPC platforms as tested under the HFSoLE project facilitated the seamless ADCIRC execution on the ARL classified IBM SP4.

Figure 5. The finite element mesh for the KAA region in the northern Persian Gulf. The ADCIRC model was applied over this grid in support of *Operation Iraqi Freedom*.

2.6. Applications/Adriatic Studies.

Wind plays a dominant role in coastal ocean processes, determining the sea state, generating storm surge and driving mixing and transport of dissolved, suspended or floating material. The performance of oceanographic models is strongly dependent on the performance of the underlying wind model. Four wind models with differing spatial resolution, physics and boundary conditions were evaluated in the Adriatic Sea over a two-month period in spring 2001: a global hydrostatic model ECMWF (European Centre for Medium-Range Weather Forecasts, 40 km resolution), a regional hydrostatic model LAMBO (Limited Area Model Bologna, 15 km), and two local area non-hydrostatic models: LAMI (Limited Area Model Italy, 7 km) and COAMPS (Coupled Ocean Atmosphere Mesoscale Prediction System, 4km). These wind models are used to drive a 2 km resolution wave model (SWAN) over the entire Adriatic. Wind and wave results are compared to observations from an oceanographic platform 16 km off the coast of Venice. Waves are also compared to observations at the oceanographic platform near Arcona and Ortona.

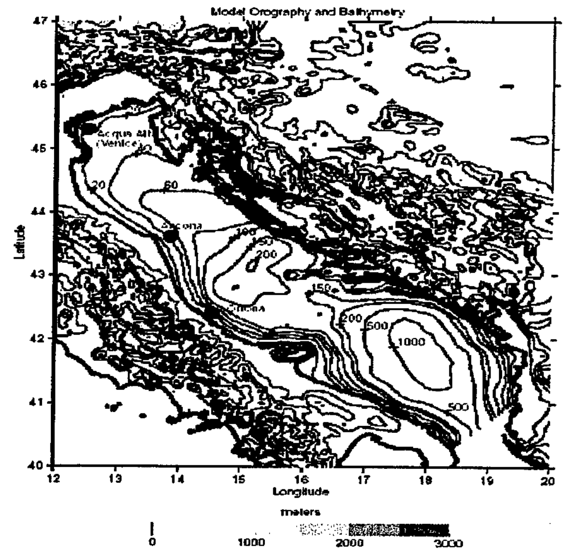

Figure 6. The gray-shaded orography is from a COAMPS 4 km wind model; isobaths are from a 2 km SWAN model. The crossed circles indicate measurements locations.

3. Results

3.1 Model Coupling.

MCEL software has been developed and tested with all models within the HFSoLE suite of models. MCEL uses a centralized server to store information and applies filters to process and transfer information to the Common Object Request Broker Architecture (CORBA) for communications.

MCEL applications include one-way coupling of a tidal circulation, wave and optics model in the Mississippi Bight.

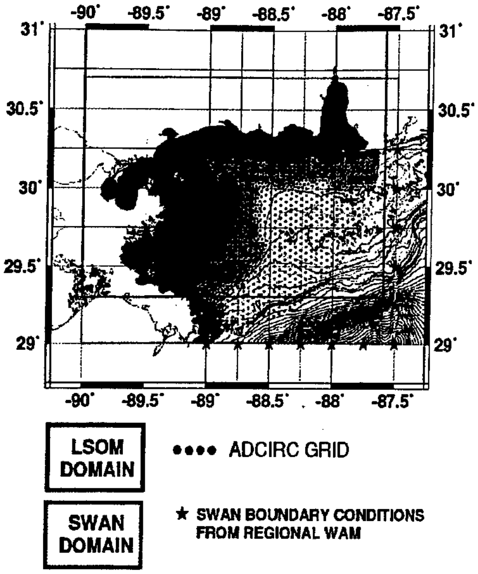

Figure 7. The grids of ADCIRC, LSOM, and SWAN are displayed for the Mississippi Bight coupled model application.

NCOM and HYCOM coupling in the Mississippi Bight provided the groundwork for more extensive coupling between these models in a new project beginning in FY04. For initial tests the vertical hybrid grid of HYCOM was re-mapped to fixed levels to facilitate the transfer of data in the vertical to NCOM. NCOM was run on a grid matching HYCOM's topography.

For a tidal inlet application, STWAVE was linked with the ADCIRC model at Grays Harbor, Washington. Including wave-current interaction improved directional predictions by STWAVE. For an open-coast application, STWAVE was linked to ADH to predict surf zone current generation. Wave stresses from STWAVE were coupled to ADH to simulate wave-driven currents (velocities are on the order of 1–1.5 m/sec in the field) and water levels and currents from ADH were linked back to STWAVE. Water levels and currents impact wave transformation. The linkages between the models were performed efficiently using MCEL. The linked models were verified using a unique data set acquired in the ERDC Large-scale Sediment Transport Facility. The validation efforts show excellent agreement between model results and measurements (error is approximately equivalent to measurement accuracy) over long time periods (months to years).

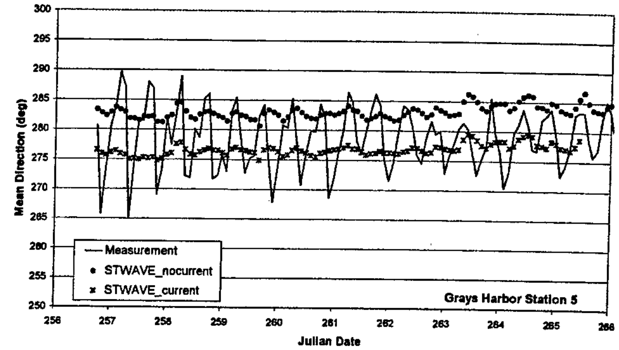

Figure 8. The improvement of STWAVE's agreement with measured values is evidence by the bright blue dotted line showing the improvement gained by coupling with ADH via MCEL.

3.2. Applications: Data Assimilation, River Database, and Boundary Conditions.

Development continues via testing of the new data assimilation techniques to fine–tune of global NCOM. Additional adjustments to entry points of river data into the NCOM continues as changes to the assimilation of data into the mixed layer affects the model's reaction to the introduction of river forcing. NCOM has provided boundary forcing data for three Naval exercises and scientists at other laboratories in addition to the Prestige and Arabian Gulf applications.

3.3. Applications: Nearshore/Surf Zone Wave and Current Modeling.

HPC applications of the STWAVE model have allowed the first long-term simulations. Surf zone applications require high resolution (on the order of meters or tens of meters) to resolve large gradients in wave heights, bathymetry, and currents. Without parallel, HPC implementation, realistic simulations are not possible. The HPC capabilities in STWAVE have been used in projects at Savannah, GA, Cape Fear, NC, Grays Harbor, WA, Willapa Bay, WA, Duck, NC, Pascagoula, MS, Camp Pendleton, CA, and Camp Lejeune, NC, and Sabine Pass, TX.

3.4. Applications: *Prestige.*

The ADCIRC and NCOM models have been called upon to provide predictions of ocean circulation and tides along the Northwest Spanish Coast after the *Prestige* oil spill. Good agreement has been found between drifter data and the output from the NRLPOM model which receives daily boundary conditions from global NCOM.

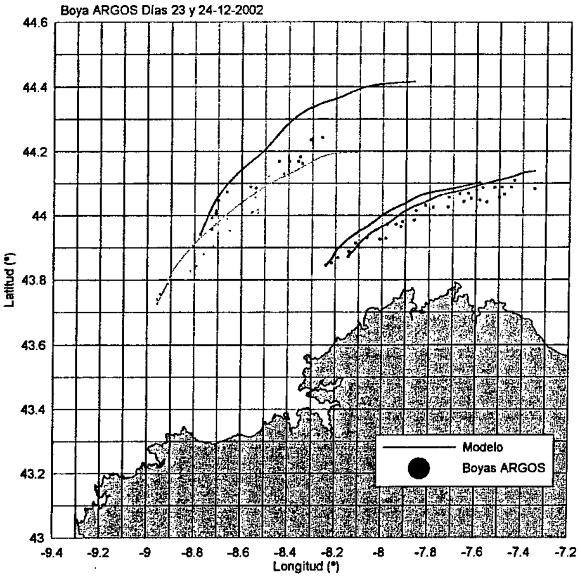

Figure 9. NCOM-NRLPOM model agreement with in-situ drifter observations.

3.5. Applications: Arabian Gulf.

In response to an informal NAVOCEANO request for sea surface height analyses, NCOM G8 data was extracted for validation in the Persian Gulf from September 2002 to April 2003. Analysis of the data indicated that the Persian Gulf was subject to wind-driven basin-scale sloshing that could under certain conditions change sea level in the northern Gulf by 1 m over 24-48 hours. A NAVOCEANO buoy in the northern Gulf provided data for verification of these findings. A comparison over the life of the buoy from its late January deployment to its loss from a collision in mid-March shows that NCOM G8 has very high fidelity in its representation of non-tidal sea level changes, giving confidence to its predictions at times and locations without in-situ monitoring.

An unclassified version of the ADCIRC KAA model developed in response to a request during *Operation Iraqi Freedom* is now constructed such that both 2D and 3D versions of ADCIRC are forced by tides and winds. A 48-hour forecast is generated in 3-hour increments following a 15 day spin-up period.

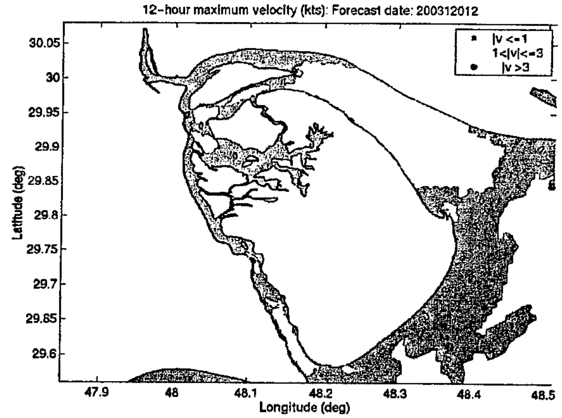

Figure 10. 12-hr tidal current thresholds (shown), along with current magnitude over direction, and elevation were typical products provided by ADCIRC for the KAA region.

3.6. Applications: Adriatic Sea.

The results of simulations performed in the Adriatic using four wind models with a 2 km resolution SWAN wave model (Signell et al., 2003) have been analyzed. On March 29-April 2, a moderate bora event occurred in the Northern Adriatic, with northeasterly winds generating waves in excess of 2 m at Acqua Alta. Major differences in the spatial structure of the wind can be seen in Fig.11 demonstrating how the four wind models resolve the bora jets due to enhancement by local orography.

The results show that the higher-resolution local area models LAMI and COAMPS have a much better amplitude response than the coarser ECMWF. The wave response is also much improved with LAMI and COAMPS with a two fold reduction in the under-estimation at the platform. The time series comparison of modeled and observed wave heights at Acqua Alta (Fig. 11) mostly reflects the differences in wind speeds. Wave heights with ECMWF are underestimated by a large degree, but with amount varying from event to event. LAMI and COAMPS perform generally better, but also with large changes in performance from event to event. At the other wave buoy locations, the improvement is more pronounced; decreasing the error from 50% to 18% at Acona and from 56% to 10% at Ortona. These results indicate that the benefit obtained by a local area wind model is regionally dependent, due to the changing influence of orography with region.

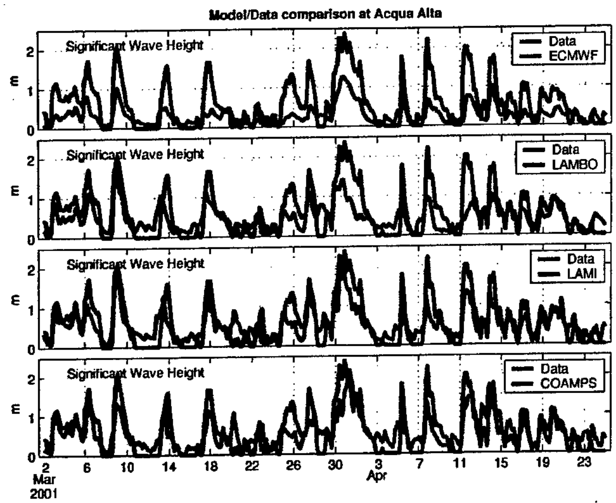

Figure 11. Wave height comparisons using forcing from four different wind models in the Adriatic.

4. Significance to DoD

The HFSoLE suite of models provides the DoD the ability to characterize the waves, tides, circulation, riverine, and optical properties in littoral waters. Additional requests continue for these models to support real world applications. The MCEL development provides a framework for efficient coupling of these oceanographic models.

Enhancements to our current operational capability for coastal ocean dynamics point in the direction of developing computational methods for high resolution ocean and atmospheric models that facilitate coupling between different scale ocean models as well as atmosphere–ocean dynamics. A direct benefit is the accurate simulation of constituents in the ocean and atmosphere. Computational costs will ultimately be minimized through efficient parallelization and algorithm optimization, thus advancing full physics models for operational predictions.

A few examples of DoD significance are directly related to the applications discussed. RADM Wilson, Oceanographer of the Navy, made a visit to COMNAVSPECOPSPAC in San Diego in which Navy SEALS brought up the ADCIRC products and extolled their value. Their primary use was for SPECOPS Mission Planning in the KAA. Secondly, Sverdrup Technology, Inc. has expressed interest in using the ADCIRC model products for planned port facility reconstruction efforts and for analyzing impacts for possible dredging at Um Qsar in the KAA, Persian Gulf.

Utilization of high resolution simulation of coastal events is a new addition to DoD operational products. As an example, the detail of the circulation depicted by ADCIRC at Um Qsar indicated the presence of a strong current shear that developed during the ebb phase of the tide. This information would have been vital to Navy swimmers, divers, and small boat operations.

5. Systems Used

The Challenge time has been divided into two equal parts under separate accounts for project investigators primarily funded through the Army Engineer Research and Development Center (ERDC) in Vicksburg, MS and the Naval Research Laboratory at Stennis Space Center, MS (NRL-SSC). At ERDC, the systems used were the Cray T3E, SGI Origin 3800, Compaq SC40 and SC45 at ERDC; at the Naval Oceanographic Office (NAVO), the IBM SP3 was the targeted platform. In addition to the fine tuning and analysis of the oceanographic models, the HFSoLE Portfolio requirements for testing on three machines and for model coupling testing were met with the use of Challenge time on the SGI Origin 3800, the Compaq SC45, and the IBM SP3. In some cases, the IBM SP4 was found to be advantageous over the SP3, as the number of processors per node is twice that of the SP3 (8 processors per node vs. 4 processors per node). This was the main reason behind the addition of the IBM SP4 to the HFSoLE Challenge Proposal for FY04.

6. CTA

The HFSoLE Portfolio is funded through the CHSSI component of the HPCMP. As a CHSSI Portfolio, it satisfies the requirement of multi-disciplinary applications, tasks and tests. HFSoLE contains 8 sub-projects under the CTA's of Climate, Weather, and Ocean Modeling and Simulation (CWO) and Environmental Quality Modeling and Simulation (EQM).

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